SOLID FREEFORM FABRICATION AND THE INTERFACE WITH DIRECT WRITE

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Abstract

An overview is given of research activity in solid freeform fabrication (SFF) in England's Northwest, concentrating on work in the Laser Group at University of Liverpool (including the Lairdside Laser Engineering Centre) and at the Laser Processing Research Centre at UMIST. This work is placed in the context of the strategy for science in the Northwest and its aims in developing and supporting industrial capability, showing that laser based approaches, including SFF, are regarded as key enabling technologies. The account also includes a consideration of the interface between SFF and other "Direct Write" technologies and outlines the recent development of Direct Write initiatives in the UK.

1. Introduction

1.1 Background on England's Northwest

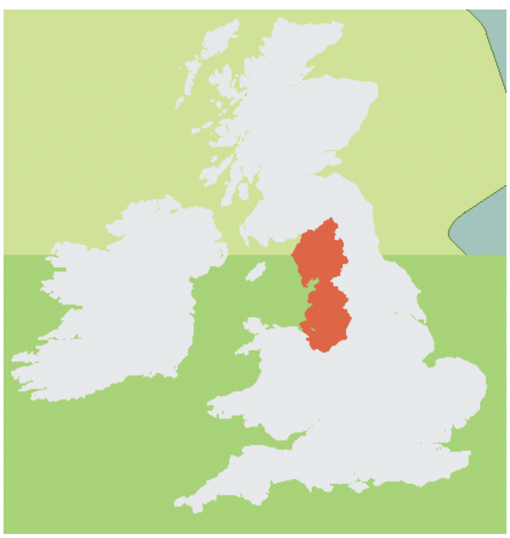

Figure 1. Northwest England region shown on map of UK and Ireland

England's Northwest is a region of high economic activity with 7 million people. It produces 10% of the GDP of the UK and has 8 universities that produce 50,000 graduates per year. This is the largest concentration of universities in Europe with a combined turnover of £1.2 billion. The Northwest is host to the strongest research base outside London and the South East.

In order to spur regional development, the UK government is proposing a degree of devolution of power from Westminster which would bring to regions such as the Northwest a degree of autonomy similar to that already enjoyed by Scotland and Wales. To this end a referundum on the setting up of a North West assembly will be held within the next few months. If passed, this would result in the establishment of a regional parliament with a devolved regional science strategy. Ahead of these developments, the North West Development Agency (NWDA at http://www.nwda.co.uk) has been carrying out science and technology developments with the objective of stimulating Northwest industry.

The Northwest is the first UK region to have developed its own science strategy (http://www.northwestscience.co.uk). The strategy has been developed by the Northwest Science Council, which brings together business, university and other science partners in the region and calls for a more effective use of the expertise in universities in the Northwest in collaboration with companies in order to develop the science, technology and engineering base in key areas (clusters of activity) identified as being essential to the sustained competitiveness of NW industry.

1.2 Details of Northwest Science Strategy

Collaboration across disciplines and across institutions with complementary skills and facilities is requested with the Northwest Development Agency (NWDA) playing a brokering and facilitating role, supported by funds to accelerate collaboration between institutions. In addition, a Foresight initiative has been initiated to ensure the science base anticipates new needs and new themes, taking advantage of opportunities where clusters and technology converge. In particular the universities in the region are asked to:

work towards 'excellence with relevance',

increase dialogue with companies and see them as strategic partners, not merely as sources of funding,

develop deeper and wider collaboration across disciplines and institutions,

explore more entrepreneurial ways of spinning out their science.

At the same time companies are asked to:

develop long term ties with selected universities and research institutions,

commit time to building relationships,

use the public research base a window on the world and on the future.

While government and public agencies are asked to:

be facilitators and enablers,

cut red tape,

improve co-ordination among themselves to help science and science-based industry succeed,

and public and private research organizations are asked to:

collaborate with companies, with universities and with each other,

build unique multidisciplinary centres of excellence based on the future needs of the key sectors.

The five clusters identified as being essential to the development of the Northwest are:

biotechnology (including pharmaceuticals and medical technology),

environmental technologies,

chemicals,

aerospace,

nuclear energy.

It is of interest that both biotechnology and energy applications are highlighted in the WTEC report on SFF in Europe while aerospace clearly falls into the identified category of manufacturing. As a result it can be confidently stated that SFF could be expected to play a significant role in three of the five main clusters identified for development in England's Northwest. As this summary shows, indeed the basis for this is already well underway.

1.3 Northwest Science strategy for Aerospace

To take the example of aerospace in more detail, the strategy document points out that the Northwest has long been identified as a global centre of excellence for the aerospace industry. The UK's main aerospace companies have a strong presence in the region, together with many tier 1,2 and 3 suppliers. There are at least 940 companies associated with the aerospace industry in the Northwest region. These employ about 48,000 people, approximately 1.7% of the regional employment. Both BAE SYSTEMS and Rolls-Royce facilities are found, representing primary strengths of the Northwest region in airframe systems design and manufacture and in design and manufacture of jet engines. Much of this activity is carried out via multi-national collaborative programmes. The strategy document points out that:

> "The Northwest has a strong science and research base, across most of the key capabilities required to support the airframe design/ aerostructures business. This includes materials processing technologies, manufacturing, rapid prototyping, business models, aerodynamics and aircraft simulation"

and it is significant that "rapid prototyping" (held here to be synonymous with technologies such as SFF) is so clearly recognized at this high strategy policy level.

The North West Universities Association has identified over 100 academic staff, each with associated research staff, whose expertise is appropriate to the aerospace sector. It is also considered that:

> "to maintain the health and prosperity of the cluster it is essential that the following are addressed:
>
> > - Research/ innovation needs: For example in Design and Integration, Business practices, aerodynamics, materials and manufacturing technologies (friction joining technologies, laser peening, laser surfacing, laser welding, rapid manufacturing, laminated structures, damage in composites, non destructive testing, polymer processing, impact resistance, creep forming, machining, robotics, virtual prototyping.
> >
> > - Skilled staff/training needs: Including education to enable identification of the opportunities offered by technology and training to develop the skills required to exploit those opportunities."

And again, it is relevant that laser processing and laser manufacturing technologies, including the production of "laminated structures" are given a high level of importance.

Finally, the action plan for aerospace involves two significant initiatives. A consortium of Northwest universities has successfully bid for £4.0m funds from the government's new Higher Education Innovation Fund to establish the Northern Aerospace Technology Exploitation Centre (NATEC). This has led to the establishment of Agile Technology Units (ATUs) in most of the universities in the Northwest, including laser based ATUs at Liverpool and UMIST. In addition, the North West Aerospace Alliance has secured widespread support for the establishment of an

Aerospace Innovation Centre (AIC).

2. Recent activity in SFF in the Laser Group at University of Liverpool, UK

The Laser Engineering Group, together with the Laser Engineering Centre at Lairdside (LLEC) at Birkenhead (Prof Ken Watkins, Dr Geoff Dearden, Dr Martin Sharp, Dr Eamonn Fearon), is one of the UK's largest university based research groups in laser materials processing with state of the art high power laser equipment for the research in welding, cutting, marking and surface treatments. Significant new areas of work include: laser ignition in internal combustion engines, laser forming and direct laser deposition. The Group is a Preferred Academic Partner to BAE Systems in the area of laser processing and has strong links with Rolls-Royce and many other companies. The Group hosts a NATEC Agile Technology Unit.

The Group published one of the first reports of SFF (then called Laser Direct Casting after work headed by the then Group leader William Steen) in 1993 [1]. The Group also published early (1992) work on variable composition laser deposited tracks produced from multiple metered powder hoppers [2 – 6].

Current projects include the design for heterogeneous SFF (called by us Direct Laser Deposition (DLD)) of components. Three cases are being considered:

1) biomimetic load bearing / matched modulus quasi-hollow structures for implantable components,
2) minimum mass/ high strength quasi hollow structures for transportation applications,
3) conformal cooling for dies and tooling applications.

The approach in each case is to investigate the usefulness of Pro Engineer *Wildfire* in developing virtual models of the required components in order to minimise the number of iterations required in the SFF of designed components for testing.

In a further project in this series, laser surface treatment techniques for the removal of internal roughness in quasi hollow titanium alloy structures are being investigated.

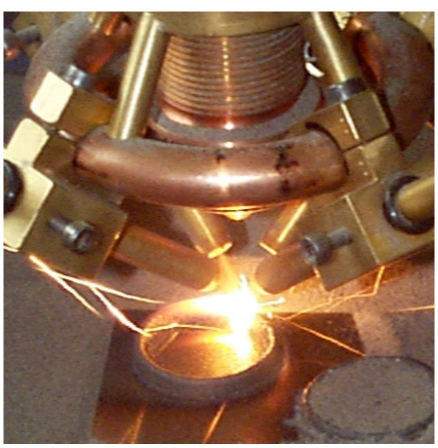
Figure 2. Deposition using the height control system

The Group is participating with 11 other UK universities in FLAVIIR, an EPSRC/BAE Systems funded programme initially running from 2004 – 2007 to develop leading edge technologies for an unmanned aerial vehicle (UAV). Direct Write will be employed synergistically with other technologies in order to impart smart functionality.

A central theme of recent reported and further ongoing work concerns non-feedback methods of layer height control in DLD [7].

Here, DLD is being examined in order to derive a method of mitigating the multivariable dependency inherent in the process and to develop a method of controlling the DLD process by restricting the physical height to which a layer can build. This has been accomplished by utilising the physical characteristics of powder transport through a nozzle to refine the powder/no powder interface at a fixed vertical position relative to the processing head (Figure 2). This refinement of the powder cloud interface causes an abrupt reduction in powder catchment efficiency in the vertical plane at a fixed position relative to the powder feed nozzle. In other words, a deposited layer will build to the top of this interface but can not build any higher due to a lack of available powder. This means that the height of the deposited layer is limited by the physical position of the powder feed nozzle and not by the other deposition parameters, allowing the layer height to be controlled by the incremental step height rather than *vice versa* (Figure 3).

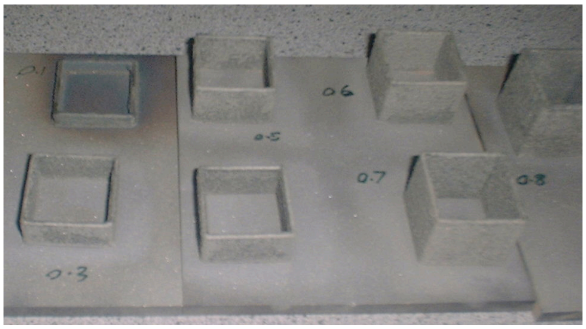

Figure 3. Clad layer height restriction of square structures showing builds made using step heights of 0.3 to 0.8mm at constant process parameters.

Attempting to control clad layer height in this way is unusual as many researchers in the field have concentrated on the control of power to the clad melt pool on the grounds that feedback control can generate an instant response from the laser at the melt pool in comparison to the lag response of the powder feed rate system.

The process has the benefit of being able to restrict deposited layer height to a high degree of accuracy without feedback mechanisms or specific software control and thus is of use in manufacturing parts where powder flow rates and delivered laser power are not highly consistent. As a result it reduces the necessary cost of associated equipment and therefore may be of benefit to smaller research establishments in academia and industry.

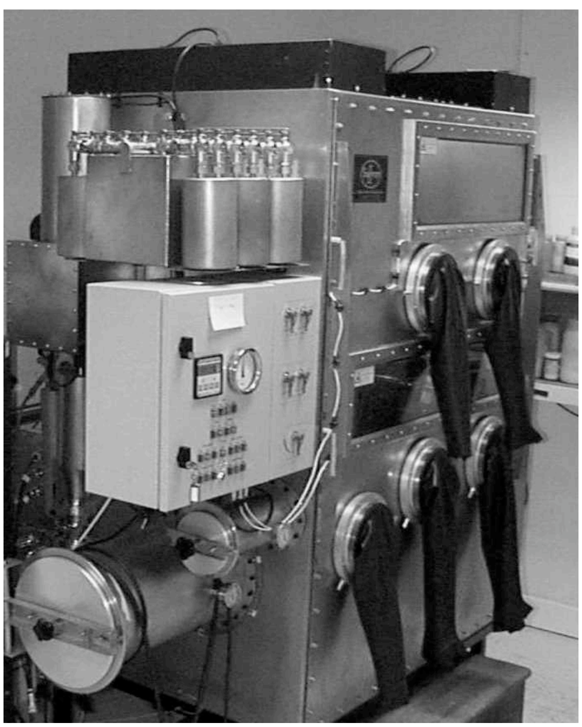

Figure 4. Experimental set up showing an anaerobic chamber used in DLD at the LLEC. This system utilises pulsed and cw Nd:YAG lasers.

Enhancement of our control systems is being carried out to allow true ‘art to part’ generation and control multiple axes and powder systems from a single PC based interface (Figure 4). Further work in this area includes investigating the effect of variation of the exit geometry of the powder feed tubes and coaxial gas nozzle. In addition, research taking place into control of the powder cloud shape in three dimensions rather than the current two will allow easy use of the abilities of the nozzle system at other angles than the vertical.

The proposed incorporation of a feedback system of temperature measurement will allow reduction of the laser power to keep a constant melt pool temperature while still taking advantage of layer height control. This will be of use in the control of cooling rates and hence microstructure formation to a greater degree than layer height restriction alone.

3. Other work in SFF at University of Liverpool

The Manufacturing Science and Engineering Research Centre (Chris Sutcliffe) is concentrating on the development of novel manufacturing processes. Current projects include the development of Rapid Manufacturing techniques for the manufacture of micro scale components, heat exchangers, smart aero-structures, pharmaceuticals, textiles, composite materials, MEMS and osteo-integrating orthopaedic implants. The centre works closely with international companies, government departments and small to medium enterprises. Details of work being carried out is contained in the WTEC visit report.

The Manufacturing Systems Research Group (Bernard Hon) is actively engaged in advanced manufacturing research on high speed machining, layered manufacturing processes and manufacturing systems analysis. A major program on Microsystems packaging has been initiated with the National Microsystems Packaging Centre funded by NWDA due to be established in Liverpool. Again, details of work being carried out is contained in the WTEC visit report.

4. Rapid Prototyping Research Activities in the Laser Processing Research Centre, University of Manchester Institute of Science and Technology, UK

The Laser Processing Research Centre (LPRC), headed by Professor Lin Li, in Manchester, UK, has been carrying out various research projects on rapid prototyping and manufacturing since 1995. The work has involved process modelling, process characterisation/optimisation and new technology development. These are summarised in the following sections.

4.1. Modelling of layered manufacturing processes

4.1.1. ***Error transformation modelling:*** It is known that for additive layer-by-layer manufacture, the geometrical accuracy is not only dependent on machine resolution but also is a function of component size, orientation and building path strategy. A significant effect is the error transformation between layers. An analytical model, validated by experimental data, was developed by the scientists in the LPRC to describe the error transformation process in layered manufacturing [8, 9]. This work provides a useful tool for the prediction of geometrical errors for additive manufacturing processes so that, a suitable part orientation and material deposition strategy can be optimised.

4.1.2. ***Modelling the direct metal deposition processes:*** Analytical models for the prediction of temperature fields, powder flow, energy distribution and deposition geometry have been developed [10 - 13]. These models have aided the understanding of direct metal deposition processes in terms of the effect of powder flow characteristics, powder geometry, laser beam energy distribution, beam spot size, deposition point stand off and types of lasers (CO_2, Nd:YAG and Diode).

4.2. Rapid Prototyping Process Characterisation and Optimisation

4.2.1. ***Comparing direct metal deposition using water- and gas-atomised powders***: Gas atomised spherical powders are currently used for direct laser metal deposition. The UMIST team has discovered that, the lower cost water-atomised powders with porous, irregular powder geometry, can give much better surface finish and energy efficiency for direct metal deposition. Both theoretical study and experimental work have been carried out to understand this phenomenon [14]. The UMIST team is currently looking into a new process based on the combination of the two different powders.

4.2.2. ***Comparing powder and wire feed direct metal deposition*:** Work has been carried out in the LPRC to investigate the difference between wire and powder feed multiple layer direct metal deposition [15]. It has been shown that the lower cost wire feeding can provide much higher deposition rate and better surface finish than the powder feeding process. The team is currently developing a combined powder and wire feeding direct metal deposition process.

4.2.3. ***Effect of beam geometry, pulse length and frequency on direct metal deposition and selective laser sintering*** [16-19]. The work has identified the influence of laser beam parameters on the material formation and properties. It has been shown that by using a pulsed beam (from nanoseconds to milliseconds) porosity can be reduced and even eliminated and surface finish can be improved compared with a CW laser beam.

4.3. Novel Rapid Prototyping Process Development

4.3.1. ***Selective laser sintering of compacted powders*:** One of the weaknesses of SLS process is the low green part density. To reduce porosity, layer-by-layer powder compacting was used. A significant improvement in both part density and geometry accuracy was demonstrated [20].

4.3.2. ***Combing self-propagating high temperature synthesis with selective laser sintering:*** Controlled solid state combustion has been used in conjunction with selective laser sintering process to enable the manufacture of high performance materials such as TiC-Al_2O_3 composite [21] from low performance feed stocks.

4.3.3. ***Micro-prototyping of metal parts by laser deposition in liquid environment***: A direct writing laser deposition technique has been developed in the LPRC [22]. The process is based on laser activation of ion deposition in an electrolyte solution in multiple layers. Copper strips have been deposited on stainless steel in such a way.

5. The interface with Direct Write and the Direct Write Association

The UK government Department of Trade and Industry has commissioned PA Consulting Ltd to produce an extensive report on additive technologies and their potential for industrial application in the UK. The report, entitled, *Direct Writing: Global Status and Opportunities for the UK in Advanced Manufacturing* was published in February 2004 (and is available at http://www.iukt.com/dwwstudyreport.htm). Impetus for the commissioning of the report came from the Direct Write Steering Group established by Inside UK Technology (http://www.iukt.com) chaired by Clive Coker with input from Neil Calder, now at the Northwest Aerospace Innovation Centre.

The study defines Direct Writing (DW) as the coming together of key technologies (nozzle techniques - especially ink jet based techniques - moulding and transfer techniques such as soft lithography and laser based techniques for modifying or adding materials) for the fabrication of two dimensional or three dimensional structures using processes that are compatible with being carried out directly onto potentially large complex shapes. The distinction made with rapid prototyping technologies is the production of functional rather than passive properties in the deposited materials. Generic steps for in situ DW are shown in Figure 5.

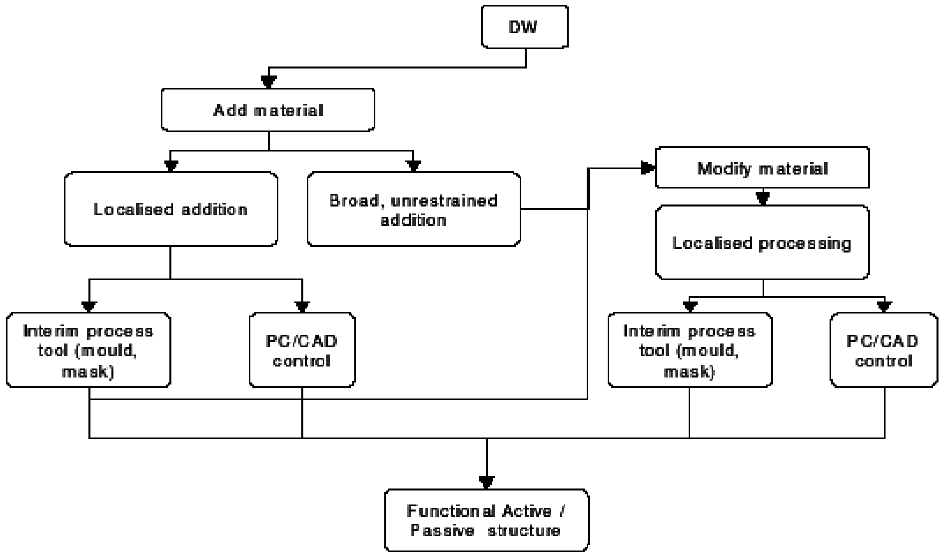

Figure 5 Classification of processes applicable to in situ DW(from http://www.iukt.com/dwwstudyreport.htm)

By situating SFF alongside these other (often non laser based) technologies and within the overall concept of DW, the report suggests a new approach within which any of these technologies, including SFF, may be thought of as being contenders for simultaneous (or sequential) use in a hybrid technology for the generation of large structures with added functionality.

In analysing the effectiveness of the UK in DW technologies, a survey of publications utilising Direct Write or Direct Writing is given which shows that the UK despite relatively modest investment to date has a place on an international scale but is behind the US, Germany and Japan in reporting results on the technology (Figure 6). Against this average picture, the UK is found on this basis to be more advanced in ink jet printing but lagging in soft lithography. The position with respect to laser based deposition techniques (despite reference to University of Liverpool's Laser Group, Lairdside Laser Engineering Centre and UMIST's Laser Processing Research Centre) remains unquantified in the report.

A wide range of potential application areas are considered with the conclusion that these offer great potential for future exploitation within the UK. The report lists the following example application areas:

In pharmaceutical or biotechnology areas:

cell handling for diagnostics,
bioscaffolds production or repair,
tissue or ceramics for dental repair,
better drugs coatings in tablets,
more accurate control of drug doses in tablets,
mass customisation of diagnostic tools for drugs discovery or genomics research.

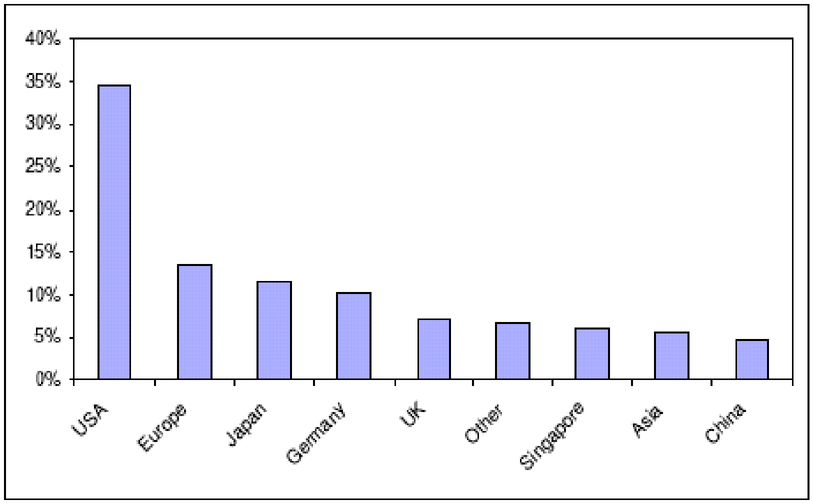

Figure 6. Publications since 2000 - 2004 mentioning Direct Write or Direct Writing as a percentage of the total by country (from http://www.iukt.com/dwwstudyreport.htm)

For automobile areas:

Lightweight conformal circuitry,
Sensors and instrumentation,
Rapid prototyping of functional structures.

For ceramics manufacture:

Late customisation,
Printed batteries,
Solar cells.

The following barriers to exploitation are identified:

Low awareness in industry,
Incomplete supply chain for a complete technological solution:
- Know how,
- Design rules,
- Materials properties,
- Qualification,
- Investment driven momentum in other (poorer) technologies,
- Perception of high investment cost.

Following publication of this report, *The Direct Write Association (DWA)* has been established with the objective of facilitating the development and deployment of cost effective direct writing technologies in the UK. Key programmes will be to:

run a communication programme,
set up pilot demonstrators,
identify leading technologies,
inform strategic research programmes.

A website at http://www.directwriting.org has been set up. *AdFab,* a regular e-newsletter for those interested in Direct Writing and additive fabrication technologies will be available by subscription. An early event, the demonstration of the nScrypt 3De direct writing system, took place at University of Liverpool in July 2004.

Conclusions

The importance of SFF is being recognised in national and regional development strategy for science and technology in the UK and in particular in England's Northwest where there is significant activity. The linking of SFF with Direct Writing is a new development in the UK that offers potential for the investigation of synergies between SFF and non laser based layer by layer technologies.

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